49959-220

SPOT GRID ARRAY ELECTRON IMAGING

SYSTEM

RELATED APPLICATIONS

The present application is related to Applicants' co-pending application serial number _____, entitled SPOT GRID ARRAY IMAGING SYSTEM, filed November 7, 2001 (Attorney Docket number 49959-170).

5

FIELD OF THE INVENTION

The present invention relates to an electron beam imaging system. The present invention has particular applicability in imaging systems optimized for automated defect inspection.

10

BACKGROUND ART

Automated inspection is a technique for measuring the integrity of an object by collecting an image of it and comparing that image to a reference (e.g., comparing a die to a data-base for photolithographic masks), to another part of that object (such as die-to-die

15 inspection for semiconductor wafers), or to a reference image (die-to-"golden image"). Disadvantageously, when conducting high-resolution inspection of large semiconductor substrates, the FOV of the imaging system cannot cover the entire substrate to be inspected, so the substrate must be moved or "stepped" across the FOV, thereby increasing inspection time. To increase throughput, some conventional automated inspection tools continuously

20 scan the substrate in one direction while optically imaging an orthogonal one-dimensional optical FOV. Once the substrate is traversed in the scanning direction, it is typically moved

in the other (cross-scan) direction by a distance of one FOV, and then its path is retraced, creating a serpentine motion path.

Other optical imaging systems for inspecting semiconductor substrates utilize a "spot grid array" to achieve high throughput. In these systems, an imager typically includes a two-

5   dimensional and periodic array of lenses, each lens imaging a spot in an object plane, such as a substrate to be inspected, upon an image plane to image a two-dimensional and periodic array of spots from the object plane upon the image plane. A sensor, such as a CCD, is provided in a conjugate image plane with a two-dimensional and periodic array of readout elements, each collecting the signal from a spot in the object plane. A mechanical system

10   moves the substrate such that as the substrate is moved across the spot array in the scan direction (the y-direction) the spots trace a path which leaves no gaps in the mechanical cross-scan direction (the x-direction). Thus, imaging of very large FOVs is accomplished by employing an array of optical elements each having a minimal FOV, rather than complex large-FOV optics. Optical imaging devices utilizing a spot grid array are described in U.S.

15   patent 6,248,988 to Krantz, U.S patent 6,133,986 to Johnson, U.S patent 5,659,420 to Wakai, and U.S patent 6,043,932 to Kusnose.

These and other previous implementations of spot-grid array concepts suffer from several limitations. To achieve the very high data-rates required for high-end inspection with all-mechanical stage scanning, a large array is required. However, some major problems

20   prevent the use of prior art technologies for large arrays, such as relatively limited focus capabilities, imaging linearity, dielectric layer interference, and limited fault detection and classification capabilities. Each of these problems will now be discussed in turn.

One limitation of prior art optical spot grid array implementations arises from the fact that inspecting with confocal imaging requires very tight focus control, which is very difficult

25   to achieve at high scan rates with large numerical aperture short-wavelength optics. To

overcome this problem, simultaneous multi-height confocal imaging is necessary. However, while taking several height-slice images sequentially, as described in the prior art, is compatible with a one frame review mode, it is not compatible with the continuous motion requirements of inspection systems.

5   Another limitation to large arrays in the prior art is the linearity requirement on the lens array, imaging optics and detector arrays. To obtain good results from a spot grid array system, close tolerances on the linearity of the optics is important – both for the microlens array and for the de-magnification optical elements. The optical spots must be located on an exactly rectilinear grid with very exact distances between the spots. Such extreme linearity is

10   difficult and expensive to achieve.

        Another limitation of prior art technology is the need to employ a coherent laser source to achieve sufficient power density for high-speed inspection. Many inspected substrates are covered by transparent or semi-transparent dielectric layers, which cause interference phenomena between the surfaces of the dielectric layers. As the thickness of

15   these layers varies across the wafer, the phase of the reflections of the coherent light from the top and bottom of the dielectric layer varies. Moreover, the interference can be either constructive or destructive. These interference phenomena cause a change in the reflected power despite the absence of defects or irregularities, limiting the accuracy of defect detection and thereby limiting the capability of the system to identify true defects.

20   A further limitation of prior art spot grid array techniques arises from the limited fault detection and classification ability resulting from the collection of light signals from a single angular section of an object. As a result, fault detection and analysis may require more than a single inspection, thus dramatically increasing the amount of data that needs to be processed and collected for reliable detection and classification of faults.

There exists a need for a low-cost, accurate, high-speed imaging system with a large FOV for reducing manufacturing costs and increasing production throughput.

SUMMARY OF THE INVENTION

5   The present invention provides an electron beam spot grid array imaging system instead of an optical imaging system, thus enhancing resolution and allowing for an analysis of the conductivity and resistance of the object.

The present invention further provides a high data rate electron beam spot grid array imaging system having a small overlap between coverage areas of spots of a spot array in

10   consecutive columns, thereby overcoming the severe linearity requirements of prior art systems.

The present invention further provides for the collection of emitted electrons from the spots formed on the substrate from several directions simultaneously, thereby improving the fault classification and detection capabilities of the imaging system.

15   Other features of the present invention will be set forth in part in the description which follows and in part will become apparent to those having ordinary skill in the art upon examination of the following or may be learned from the practice of the invention. The advantages of the invention may be realized and obtained as particularly pointed out in the appended claims.

20   According to the present invention, the foregoing and other features are achieved in part by an imager comprising an electron beam generator for simultaneously irradiating an array of spots spaced apart from each other on a surface of an object to be imaged, and a detector for collecting signals resulting from the interaction of the spots with the surface of the object to form an image of the irradiated portions of the object surface. A mechanical

25   system moves the substrate in a direction nearly parallel to an axis of the array of spots such

that as the substrate is moved across the spot array in the scan direction, the spots trace a path which leaves no gaps in the mechanical cross-scan direction.

Additional features of the present invention will become readily apparent to those skilled in the art from the following detailed description, wherein only the preferred

5   embodiments of the present invention are shown and described, simply by way of illustration of the best mode contemplated for carrying out the present invention. As will be realized, the present invention is capable of other and different embodiments, and its several details are capable of modifications in various obvious respects, all without departing from the invention. Accordingly, the drawings and description are to be regarded as illustrative in

10   nature, and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

Reference is made to the attached drawings, wherein elements having the same reference numeral designations represent like elements throughout, and wherein:

15   Figures 1a-1e schematically illustrate imaging systems in accordance with embodiments of the present invention.

Figure 2 depicts a spot array on the surface of the object plane produced by the systems of Figures 1a-1e.

Figures 3a and 3b depict spot arrays according to embodiments of the present

20   invention.

Figure 4 schematically illustrates an imaging system in accordance with an embodiment of the present invention utilizing multiple detectors.

Figure 5 schematically illustrates an imaging system in accordance with an embodiment of the present invention wherein two substrates are imaged simultaneously.

DESCRIPTION OF THE INVENTION

An embodiment of the present invention will now be described with reference to Fig. 1a. An electron source 100 or 100a generates an ordered array of electron beams (also called "e-beams") 110 or 110a to irradiate a substrate 160 to create a spot array 150 on the surface

5   of substrate 160. The spot array on the substrate 160 can be generated either by employing an electron-optical system for imaging and beam separation (e.g., a projection apparatus comprising electron source 100 and a beam splitter 120), or by side illumination using electron source 100a.   Detector 130 collects secondary electrons (SE) or backscattered electrons (BE) from substrate 160, and imager 140, which is analogous to conventional

10   systems used in low-electron energy microscopy (LEEM) techniques, provides an SE or BE image of substrate 160.

Substrate 160 is carried on a mechanical stage 165 which is moved in the y direction in a direction which is nearly parallel to one of the axes y of the array of spots 150. The deviation from parallelicity is such that as substrate 160 is moved a distance substantially

15   equal to the length L of the spot array in the scan direction y, the spots trace a path which leaves no gaps in the mechanical cross-scan direction (the x direction), thereby ensuring that the entire surface of substrate 160 is irradiated.

Electron source 100, 100a can employ well-known techniques such as multiple cathodes within an electron imaging column, each cathode producing an e-beam 110, 110a.

20   Alternatively, as shown in Fig. 1b, a membrane 101 having an array of pin-holes 102 corresponding to e-beams 110, 110a can be provided to block an area flux of electrons 103 produced by an area flux electron source 104, resulting in only e-beams 110, 110a reaching substrate 160.

In another embodiment of the present invention, as illustrated in Fig. 1c, a

25   conventional photocathode 107 is illuminated with an array of optical spots 108

(corresponding to e-beams 110, 110a) generated by a light source 105 and focused with a microlens array 106. Photocathode 107 generates e-beams 110, 110a in response to optical spots 108. Microlens array 106 can be a single array of lenses, or multiple arrays arranged in series, as per coventional optical techniques, so the optical paths of the individual lens

5   elements from the separate arrays form a compound lens. Such an arrangement results in arrays of compound lenses having a higher numerical aperture than can be obtained with arrays of single lenses. Such compound micro-lens arrays can be mechanically assembled by stacking individual lens arrays, or manufactured by, for example, well-known MEMS (micro-electro mechanical systems) manufacturing techniques.

10   In a further embodiment of the present invention, illustrated in Fig. 1d, electron source 100, 100a comprises a collimated electron source 200 for generating a wide collimated electron beam 210 and a plurality of electron-blocking masks 220-240 to act as the equivalent of optical microlenses for converting wide collimated beam 210 into an array of focused e-beams 110, 110a for forming spot array 150 on substrate 160. Each mask 220-240 is a

15   metallic planar membrane having an array of pinholes 221, 231, 241 corresponding to each e-beam 110, 110a. Masks 220-240 are substantially parallel to each other and aligned such that their pinholes 221, 231, 241 are concentric. Each mask 220-240 has pinholes of a different diameter than the other masks. Thus, the diameter d_1 of pinholes 221 is different from the diameter d_2 of pinholes 231, which is different than the diameter d_3 of pinholes 241. Each

20   mask 220-240 is connected to a conventional voltage source VS for holding each of them at a different voltage V_1-V_3, thereby creating a microlens array for electrons.

As the performance of electron optics is limited for off-axis electron beams, in a further embodiment of the present invention, an aperture membrane 250 having pinholes 251 corresponding to pinholes 221, 231, 241 in masks 220-240 is placed between collimated

electron source 200 and masks 220-240 (see Fig. 1e). Aperture membrane 250 thus serves as an array of apertures for the individual "lenses" of the electron microlens array.

The collected electrons (back-scattered or secondary) can be collected by detector 130 using LEEM techniques. In one embodiment of the present invntion, the electron imaging

5   system composed of electron source 100, 100a and beam splitter 120 is used to image an area of substrate 160 upon a two-dimensional electron detector array (such as a conventional multi-channel plate (MCP) coupled to a detector array such as a CCD, or a scintillator coupled to an image intensifier and CCD), all of which are part of detector 130. In standard LEEM, there is a severe challenge of obtaining a fine resolution in a large FOV. However,

10   when generating discrete spots as in the technique of the present invention, the LEEM resolution only has to be sufficient to prevent cross-talk between the spots. Furthermore, high-speed e-beam inspection can be limited by thermal and radiation damage effects created by the large electron current needed to collect the sufficient signal for the high-data rate imaging. However, the use of a very large number (on the order of 10^6) of parallel sources

15   allows a dramatically lower data rate for each source (100's of Hz to several KHz Vs. 10's of MHz) and therefore use of a much smaller current (on the pico-amps scale vs. tens of nano-amps).

Figure 2 schematically depicts spot array 150 in the substrate (object) plane. For simplicity, Fig. 2 shows an 8 wide (a-h) by 6 deep (1-6) array of spots. When practicing the

20   present invention, the array typically comprises at least several hundred e-beams, resulting in a corresponding number of spots. The shift in the mechanical cross-scan x direction between the centers of spots in consecutive lines determines the pixel size in the x direction (i.e., the projection p_x on the x-axis of the distance between the e'th spot in the first line e1 and the e'th spot in the 2nd line e2). The pixel size reflects how densely substrate 160 is sampled.

25   To obtain continuous coverage of substrate 160, the last spot in column d6 must trace a path

no more than one pixel away in the cross-scan x direction from the tangent of the first spot in an adjacent column (c1). The pixel size in the mechanical scan y direction p_y (not shown) is determined by the distance traversed between the spot center of a given spot between two consecutive samplings of detector 130; that is, the distance between the center of a spot f4 at

5   time 0 ("f4t0") and the same spot one sampling interval later ("f4t1"). This distance is determined by multiplying the stage velocity and sampling interval.

Substrate motion via stage 165 can be achieved by any means ensuring accurate and linear motion, such as can be obtained from a conventional interferometer-controlled stage with linear motors and air-bearings, commercially available from Anorad Corporation of

10   New York. To correct the residual inaccuracy such as that created by mechanical vibrations of stage 165, a servo 170 can be included to control an element for moving the spot array and compensating for the substrate mislocation. In the embodiment of Fig. 1a, the movable element may be the beam splitter 120. In another embodiment of the present invention, the movable element is the electron source 100a itself. In the embodiment of Fig. 1c, the

15   movable element can be microlens array 106. The angle of incidence upon the back pupil of lens array 106 may be changed by means of a movable mirror, an electro-optic or an acousto-optic element in the optical illumination path.

In the embodiment of Figs. 1a and 2, the shift in the mechanical cross-scan x direction between the centers of spots in consecutive lines determines the pixel size in the x direction

20   (e.g. the projection p_x on the x-axis of the distance between the e'th spot in the first line e1 and the e'th spot in the 2nd line e2). Moreover, the last spot in one column (d6) passes a distance of one cross-scan pixel (p_x) away from the path of the first spot of an adjacent column (c1). Therefore, the distance between the spot columns or the "spot pitch" determines the number of lens rows in the array (n_r).

In an alternative embodiment of the present invention, a larger number of rows (n_r) are used, and the e-beam array is tilted such that the x-axis separation between the paths of spots in consecutive rows is a fraction (f) of the pixel-size (p_x/f). The substrate velocity is chosen such that it transverses a distance in the y-axis a factor f larger than a single pixel

5   (p_y/f). Referring now to Fig. 3a, wherein a simple scan pattern is shown, for a given pixel created by spot $b1_1$, the subscript stands for the writing period, the y neighbor on top is $b1_2$, and the x neighbor on the left is $b3_n$ where $n=s/p_y$ (to create a rectangular array, the value of s/p_y needs to be an integer). In Fig. 3b, however, an interlace scanning pattern is created (it shows f=2 for simplicity). In this case, $b1_1$ and $b1_2$ will be separated by a distance of $2p_y$,

10   where the adjacent pixel to $b1_1$ will be $b2_n$ and $n=s/2p_y$. $b1_2$ will be shifted relative to $b1_1$ in a diagonal with a slant of 1/f. Therefore, for a large f the separation is mainly in the y direction. The result is a continuous coverage of the substrate achieved by an interleaving of f periodic structures offset in both axes.

An advantage of the interleaving of this embodiment of the present invention is a

15   larger number of individual spots in a given FOV. Therefore for an identical pixel-rate requirement the array read rate ("frame-rate") can be lower since there are more elements in the array. When practicing this embodiment, close tolerances on the linearity of the motion of the mechanical stage and on the inter-spot spacing are necessary.

To obtain good results when practicing the spot array concept of the present

20   invention, close tolerances on the linearity of the electron optics is important. The spots must be located on an exactly rectilinear grid with very exact distances between the spots. For example, if we have a grid 1000 rows deep, the thousandth row spot of column n must pass accurately near the location which was viewed by the first row's spot of column n-1. Assuming a desired accuracy of 1/10th of a pixel, this implies linearity of one tenth of a pixel

25   over the length of the FOV. Where the e-beam pitch is equal to 100 pixels, the linearity

requirement is therefore $1:10^6$ (1000 rows * 100pixels pitch / 0.1 pixel tolerance = 10^6). This requirement for extreme accuracy is problematic if mechanical vibrations are present.

In a further embodiment of the present invention, this severe linearity requirement is removed by creating a small overlap between the coverage areas of the spots in consecutive

5 columns, thereby reducing the deleterious effects of mechanical vibration on the system. This is achieved by providing additional rows of spots; e.g., adding rows "7" and "8" in the spot array of Fig. 2. Furthermore, in most automated inspection systems, such as Applied Materials' WF-736, the image comparison is done between two locations along the substrate scanning direction. The additional rows of pixels of this embodiment enable pixels generated

10 by individual columns to be compared to pixels generated by the same column. Moreover, image processing algorithms typically require operations on a given pixel's neighbor. The overlap between columns (i.e., the additional rows of pixels) is preferably sufficient to provide "spare" pixels (typically 1 to 5 pixels) to ensure that neighboring pixels used for purposes of an algorithm are all from the same column. In this way, spot d6 does not have to

15 be compared with a remote spot such as c1. This embodiment essentially makes the spots of each column into an individual data-path. It is also compatible with the use of a modularized image processing approach; for example, each column feeding into a separate image processing module. Such a modularized approach simplifies and speeds processing.

In this embodiment of the present invention, the linearity requirement is reduced to

20 the distance between rows of an individual column which pass in the vicinity of each other. In the non-interlaced basic approach this distance is one spot pitch. For the case described above this is a linearity requirement of 1:1000 (100 pixels pitch / 0.1 pixel tolerance). If interlacing is used (see Fig. 3b) the linearity requirement is multiplied by the interlace factor and thus becomes 1:10,000 for an interlace factor of 10.

In yet another embodiment of the present invention, electrons emitted from the spots formed on the substrate are collected from several directions simultaneously. This multi-perspective imaging technique enables defect detection and classification to be conducted with greater accuracy, since certain types of defects emit electrons (e.g., backscattered and/or

5   secondary electrons) in characteristic known directions. Thus, the presence or absence of emissions of a particular type of electron at a particular angle in relation to the substrate can be used to determine the presence of a particular type of defect.

The multi-perspective imaging of this embodiment of the present invention can be achieved by placing several detectors 430a, 430b at different angles with relation to substrate

10   160, as depicted in Fig. 4. Any conventional detector systems can be employed that are capable of imaging the entire field of view of substrate 160 with the resolution of the separation of spots 150. Thus, a portion of the signals (i.e., emitted electrons) resulting from the interaction of spots 150 with the surface of substrate 160 emitted at a first angle are collected by detector 430a, and a portion of the signals resulting from the interaction of spots

15   150 with the surface of substrate 160 emitted at a second angle are collected by detector 430b.

In a further embodiment of the present invention illustrated in Fig. 5, two corresponding substrates 640a, 640b, such as two identical dies from the same wafer, are placed on a movable stage 650, and one die is used as a reference for inspection of the other

20   die. Electron sources 600a, 600b, which can be any one of the electron sources described above including conventional mini-columns or micro-columns, provide e-beams that impinge upon substrates 640a, 640b, as through beam splitters 620a, 620b as necessary, to irradiate identical arrays of spots on substrates 640a and 640b.

Signals from substrates 640a and 640b are collected by detector arrays 660a, 660b,

25   and the resulting images compared by processor 670 to determine if defects exist on one of

the substrates 640a, 640b. For example, the gray levels of corresponding pixels of the two images are compared, and if they differ by more than a predetermined threshold amount, processor 670 determines that a defect exists at that pixel location. As in previous embodiments of the present invention, movable stage 650 moves such that substantially the

5 entire surface of each substrate 640a, 640b is irradiated and imaged. However, an advantage of this embodiment of the present invention is that since both substrates 640a, 640b undergo the same vibrations of stage 650, the unwanted effects of that vibration are not relevant, and do not need to be compensated for, as they do in the other embodiments described herein.

The following examples illustrate the calculation of various parameters relevant to the

10 practice of the present invention:

Definitions:

FOV – Field-of-view in microns on substrate (assume square)

D - Pitch between spots on substrate in microns

p – Pixel size on substrate in microns

15 n_y and n_x – number of rows and columns in array respectively

N – total number of spots in array

DR – Data-rate requirement (pixels/second/array)

FR – Frame-rate requirement (array-read/second)

V – stage velocity in y direction in microns/sec

20

Since $FOV = D * n_x$, $n_y = D / p$. Thus, the total number of spots N to be irradiated is calculated by:

$$N = n_x * n_y = (FOV/D) * (D/p) = FOV / p$$

25

For a given data-rate requirement (DR) the frame rate (FR) and hence stage velocity required are:

$$FR = DR / N = DR*p / FOV \quad \text{and} \quad V = FR*p = DR*p^2 / FOV$$

5 Example 1:

FOV = 1mm = 1000micron

DR = 10 Giga-pix/sec = 10^{10} pix/sec

P = 100nm = 0.1 micron

⇨ N= 1000/0.1=10,000 =10^4 => a 100 by 100 array;

10 ⇨ FR = $10^{10}/10^4$ = 10^6 = 1 mega-frames/second

⇨ V = 10^6*0.1micron = 100mm/sec

For a given pixel size, increasing the FOV is key to obtaining a larger number of pixels in the array, and hence to reduced frame-rates and stage velocity requirements (when
15 using interleaving as shown in Fig. 3b, the number of rows and hence array elements increases and the frame-rate goes down, but the stage velocity requirement remains unchanged). This is an issue when using electron beam imaging and an electron-imaging column to focus multiple electron beams.

20 Example 2:

If the pixel size is reduced to 10nm and the FOV is increased to 10mm, the total number of array spots is N=10,000/0.01=10^6. Keeping the frame-rate (FR) at 10^6 frames/second, the data rate (DR) of the present invention becomes 10^{12} pixels/second or one Tera-pixels/second. The stage velocity (V) at this DR is 10mm/sec. This system according
25 to the present invention is three orders of magnitude faster than any prior art system. Of

course, such a system requires conventional image acquisition and image processing systems capable of handling a high data-rate.

The present invention can be practiced by employing conventional materials, methodology and equipment. Accordingly, the details of such materials, equipment and

5 methodology are not set forth herein in detail. In the previous descriptions, numerous specific details are set forth, such as specific materials, structures, chemicals, processes, etc., in order to provide a thorough understanding of the present invention. However, it should be recognized that the present invention can be practiced without resorting to the details specifically set forth. In other instances, well known processing structures have not been

10 described in detail, in order not to unnecessarily obscure the present invention.

Only the preferred embodiment of the present invention and but a few examples of its versatility are shown and described in the present disclosure. It is to be understood that the present invention is capable of use in various other combinations and environments and is capable of changes or modifications within the scope of the inventive concept as expressed

15 herein.